River ice monitoring from optical and SAR remote sensing perspective: Advances, challenges and opportunities

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Globally, more than one third of rivers are covered by ice and snow during winter (e.g. Figure 1A).[1] Due to climate warming, the duration of ice cover across most regions of the Northern Hemisphere has exhibited a significant decline, with the rate of decrease accelerating nearly five times over the past 150 years.[2] River ice formation fundamentally shapes distinct chemical and biological environments, directly influencing the transport of nutrients, heat, and moisture, while indirectly affecting material cycling between environmental elements and organisms.[3] Unfortunately, the freezing and melting processes of river ice present significant regional variations due to differences in geographic location and hydrological conditions, notably increasing the complexity of ice monitoring tasks. In this regard, remote sensing, as a cutting-edge observation technology, facilitates the monitoring of large-scale and long-term dynamic ice patterns. In comparison with conventional in-situ observation methods, remote sensing offers the ability to respond rapidly to changing conditions, positioning it as one of the most important tools for ice monitoring in recent years.

PRINCIPLES AND METHODS OF OPTICAL AND SAR REMOTE SENSING FOR RIVER ICE MONITORING

The river ice phenomenon (Figure 1B) comprises the entire process from formation to dissipation. From the data source perspective, river ice monitoring can be divided into optical and polarimetric synthetic aperture radar (SAR) remote sensing. Optical satellites with multispectral sensors covering visible to near-infrared wavelengths offer broad imaging and frequent revisits,

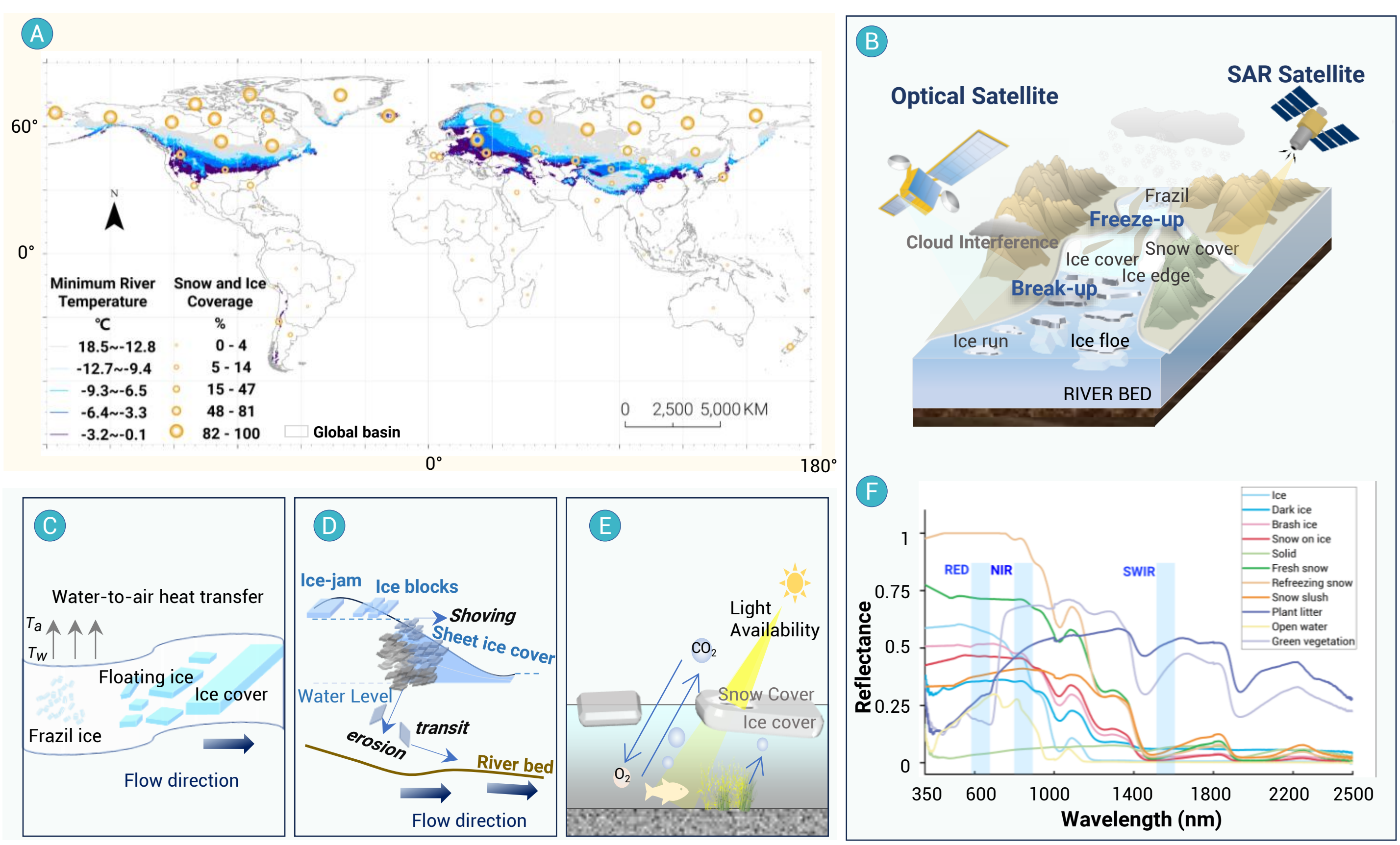

Figure 1. River ice monitoring with optical and SAR remote sensing (A) Global map of river ice extent. The yellow circles represented the percentage of ice/snow cover in global watersheds, and the blue lines showed the minimum temperature in global rivers. (B) Schematic diagram of river ice formation and ablation process based on remote sensing observations. (C) Integration of remote sensing with river ice physical models. (D) Mechanisms of ice jamming flood. (E) Winter CO_2 emissions from rivers. (F) Refined reflectance of river ice.

making them widely used in ice and snow monitoring. Different river ice types have distinct spectral characteristics (e.g. Figure 1F). Spectral-based river ice identification methods fall into four categories: (1) Visible and panchromatic bands from sensors like Landsat are utilized to visually interpret river ice distribution patterns, though the process is manual and cannot be automated. (2) Ice/snow indices use reflectance differences in green and near-infrared bands to extract ice extent and duration. These are simple and scalable but sensitive to threshold selection, causing possible ice extraction errors. (3) Machine learning methods integrate spectral and texture features for automatic classification during ice formation and melt, but face limitations in global/interdecadal studies due to sample scarcity and computational demands. (4) Methods based on quality bands to identify snow/ice pixels. These are time-saving and widely adopted, though dark ice in melt seasons may be overlooked, and performance is affected by lighting/weather conditions.[1]

In contrast to the limitations of optical images, SAR offers cloud-penetrating, all-weather imaging. Various SAR-based methods analyze scattering signals at the ice-water interface and use polarization decomposition to enhance detection by revealing surface texture and water content. Due to river turbulence, more ice types form, which C-band (RADARSAT-2, Sentinel-1) and L-band (ALOS PALSAR) sensors can capture. These polarimetric SAR images were analyzed by using both coherent and incoherent methods. Incoherent methods like model-based (Freeman-Durden, Yamaguchi) and algebraic (Cloude–Pottier) decompositions effectively reveal scattering mechanisms. Parameters such as entropy, anisotropy, and alpha-angle help distinguish ice from water. Cross-polarized signals (HV, VH) indicate freezing periods, while co-polarized signals (HH, VV) monitor ice jams and floods, providing valuable insights into ice dynamics and associated hydrological hazards.[4] Polarimetric entropy regression has shown potential for ice thickness detection using C-band SAR. Despite advantages, SAR processing is more complex. Free tools like SNAP, PolSARpro, and MapReady exist, but the preprocessing of SAR data requires a basic understanding of the physical scattering mechanisms of ice surface, hindering the wider application of SAR images. Furthermore, the scarcity of historical SAR data compared to optical remote sensing images significantly limits their use in retrospective analyses. Nevertheless, since the 21st century, SAR resolution and coverage have improved, and its integration with optical imagery increasingly supports 3D observations of ice extent and thickness.

CHALLENGES IN RIVER ICE MONITORING USING OPTICAL AND SAR REMOTE SENSING

Observational errors due to water quality variations. Rivers around the world exhibit varying water quality characteristics due to unique hydrological conditions and human activities, resulting in natural color differences in water bodies. When image recognition techniques are used to identify river ice types, varying turbidity levels across different rivers—such as the Yellow River in China and the Amu Darya in Turkmenistan—can affect spectral reflectance, making newly formed ice difficult to distinguish from open water.[1]

Limitations in temporal resolution. High-resolution satellite imagery, such as Sentinel-1/2 satellite, provides repeat global surface coverage every 5 or 6 days. However, this temporal resolution is insufficient for studying the ice freeze-up and break-up process. For example, the ice break-up process typically involves rapid and large-scale ice transport and ice dam formation (Figure 1D), making it difficult to capture the entire event. To this end, efficient data fusion methods are required to generate high-quality observational datasets which improve the temporal resolution of imagery to 1-3 days and fulfil the technical specifications outlined by the Global Climate Observing System.

Monitoring of small rivers during ice seasons. Small rivers are less influenced by human-induced water flow regulation, so that they can better represent the natural cooling mechanisms and thermal growth processes of river ice under specific climatic and geographical conditions. However, remote sensing imagery with limited spatial resolution makes it difficult to monitor small rivers, especially when the river width is less than 500 meters,[5] resulting in reduced monitoring quality. Moreover, ice cover prevents rivers from releasing carbon dioxide into the atmosphere. Ignoring the contribution of these narrow rivers would exclude the majority of rivers globally, significantly affecting the estimates of riverine carbon emissions and the understanding of winter river Gross Primary Production (GPP).[3]

THE PROSPECTS FOR RIVER ICE RESEARCH USING REMOTE SENSING IMAGES

Synergistic observations from multi-source remote sensing data. Comprehensive and accurate river ice monitoring requires high-quality and timely observational data. Multi-perspective observations from in-situ stations, field surveys, airborne sensors, and satellite sensors provide the foundation for collecting long-term optical and SAR imagery. These observations are instrumental in establishing comprehensive three-dimensional monitoring of river ice, thickness, snow depth on ice, and ice flow dynamics. Considering the differences in imaging mechanisms between SAR and optical remote sensing imagery, the nonlinear radiometric discrepancies between them may cause distortions in the fused spectral and texture features. Advanced methods should mitigate limitations caused by observation frequency, enhancing the ability to monitor river ice formation and evolution.

Integration of remote sensing with hydrological models. Field observations have documented river ice processes such as the appearance of fine ice crystals, heat loss leading to aggregation, and eventual cover formation(Figure 1C). Existing hydrological models simulate river ice formation, with a focus on ice jam events when transport exceeds capacity (Figure 1D). Remote sensing, despite uncertainties in vertical angles of ice and snowpack, combined with mechanistic models based on heat and hydraulic conduction equations, can better quantify river ice and snow accumulation/melting processes. Furthermore, combining remote sensing with climate models presents an opportunity for exploratory projections of river ice evolution over the next 100 years, offering insights into potential global responses to climate change.

Strengthening the understanding of river ice models and their relationship with watershed ecology. The river ice period is shaped by topographic and climatic factors, with its seasonal dynamics showing variations. However, ecological studies often overlook the role of winter ice cover dynamics in river functioning, which limits the understanding of winter watershed ecological functions significantly, as seen in Figure 1E. Unfortunately, the shortening of river ice duration due to climate warming has been confirmed. Studying the relationship between river ice dynamics and winter productivity, as well as animal habitats and aquatic food webs, is crucial for watershed ecological management and conservation.

CONCLUSION

Remote sensing as an efficient earth observation technology provides high-resolution spatiotemporal data for monitoring river ice. This paper introduces optical and SAR-based monitoring methods, discusses their limitations, and outlines future research directions. Enhancing watershed management will rely on integrating emerging techniques and deepening understanding of river ice dynamics.

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DECLARATION OF INTERESTS

The authors declare no competing interests.